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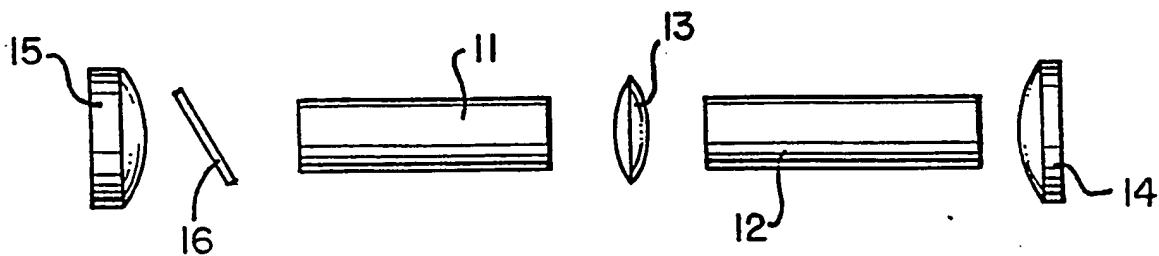
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## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: HIGH POWER ND:YLF SOLID STATE LASERS



## (57) Abstract

A high power Nd:YLF solid state laser is constructed by placing a plurality of Nd:YLF solid state rods (11, 12) in series within a laser resonator. Each rod (11, 12) is mounted in a pumping chamber for providing laser action. A spherical lens (13) may be incorporated within the resonator as required for establishing with the resonator mirrors (14, 15) a large intra-cavity beam diameter. A cylindrical lens is provided within the resonator as a separate element or combined with the spherical lens (13) to compensate for astigmatism in the thermal focusing of Nd:YLF rods. Alternatively, the rods may be used in pairs with a half-wave plate between them to provide for compensation of astigmatism. A laser capable of high  $TEM_{00}$  mode output power may be achieved by these arrangements.

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HIGH POWER Nd:YLF SOLID STATE LASERSBACKGROUND OF THE PRESENT INVENTION5 Field of the Present Invention

The present invention relates to solid-state lasers and, more particularly, to improvements in solid state lasers having low thermal focusing and low thermal birefringence loss.

10 Background of the Present Invention

High power  $TEM_{00}$  solid-state laser output, either CW or Q-switched, is required for many commercial or research and development applications. Large active mode volume in the solid-state lasing crystal is a critical requirement in achieving this goal. Unfortunately, the active lasing volume in Nd-doped YAG (the most popular solid-state laser host) has been limited by its thermally-induced focusing (caused by large refractive index variation with temperature) and by thermal birefringence loss which increases quadratically with radial 15 position in cylindrical laser rods. Therefore, CW  $TEM_{00}$  power over 30 watts remains unavailable from any commercial solid-state laser system today.

20 Certain characteristics of the crystal Nd:LiYF<sub>4</sub> (YLF) have been shown in recent studies to be advantageous. This crystal has very low thermal focusing and, because it is a birefringent crystal, its lasing output is naturally polarized and hence unaffected by thermal birefringence loss. In addition, Nd:YLF lasers have achieved  $TEM_{00}$  power outputs 25 comparable to Nd:YAG with equivalent sized rods.

30 Thermal focusing in Nd:YLF Laser rods, although small, nevertheless is astigmatic, i.e. its magnitude and sign are different in the X and Y directions. This is conventionally corrected by utilizing a cylindrical lens to produce an output beam that is circularly symmetrical. This cylindrical lens is 35 in addition to the spherical lens used to expand the beam for large mode volume.

An object of the present invention is to increase the

$TEM_{00}$  power output of solid state lasers having low thermal focusing and low thermal birefringence loss.

A specific and further object of the present invention is to increase the power output of Nd:YLF solid state lasers.

5 Yet a further object of the present invention is to produce a circularly symmetrical output without the use of a cylindrical lens.

#### SUMMARY OF THE INVENTION

10 In accordance with the invention, a high power solid state laser comprises a laser resonator and a plurality of solid state laser rods mounted in pumping chambers. The rods are arranged in series and are constructed of a material having low thermal focusing and low thermal birefringence loss. Means 15 are arranged within the resonator for establishing a large intra-cavity beam diameter and active volume, and, thereby, a high  $TEM_{00}$  laser output.

20 The laser rods are made of solid state Nd:YLF and the laser polarization is aligned along a crystal A axis to produce an output at 1053nm. A first Nd:YLF rod is mounted in a pumping chamber within the resonator. A second Nd:YLF rod is mounted in a second pumping chamber collinearly with the first rod. The laser energy output of one rod is focused relative to the other rod by lens and cavity mirror means so as to establish a large intra-cavity beam diameter and active volume and, thereby, a high  $TEM_{00}$  laser output.

25 Although arranged in series and aligned collinearly along a central laser axis, the rods are rotated 90° from one another about the laser axis. A half-wave plate is aligned collinearly along the laser axis positioned between the pair of rods and oriented to rotate the laser polarization by 90° thereby maintaining the appropriate laser wavelength output. As a result, the astigmatic beam of one rod is corrected by the astigmatic focusing of the second beam so that a circularly 30 symmetrical output beam is created.

35 For a better understanding of the present invention, reference is made to the following description and accompanying

drawings while the scope of the invention will be pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

5 Figure 1 is a representational view of the primary parts of the laser of the present invention;

Figure 2 is a block representation of the laser of Figure 1 operating in a Q-switched mode;

10 Figure 3 is a representational view of a Nd:YLF laser rod showing the astigmatism in the X and Y directions of the thermal focusing; and

Figure 4 is a representational view of two collinear Nd:YLF laser rods and a half-wave plate to produce circularly symmetrical output.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

In order to enhance mode volume of a solid state laser, it is necessary to utilize completely the area of the laser rods so that intra-cavity beam diameter is expanded as much as 20 is allowed by the limitations of rod diameter. However, in prior art YAG lasers this increase in beam diameter has also been limited by its thermally-induced focusing and birefringence loss. This limitation of beam expansion is overcome according to the present invention by the use of Nd:YLF rods, 25 which have nearly zero thermal focusing and zero birefringence loss.

In Figure 1 there is shown a plurality of Nd:YLF laser rods placed in series inside a resonator in order to effectively increase the overall rod length so as to achieve a large active volume and, thereby, a higher  $TEM_{00}$  laser output.

30 Two such rods are shown in series within an arrangement 10. The rods may be identically sized and shaped and, for achieving  $TEM_{00}$  output, the rods are placed within a standard resonator such as of the Quantronix 4000 series. The rods are 35 4X79 mm and are mounted in pumping chambers (not shown) in series within the resonator.

In this series arrangement, the rods are mounted

collinearly with convex lens 13 therebetween. The resonator includes high reflectance mirror 14 at one end and output mirror 15 at the other end. Element 16 represents an intra-cavity Brewster plate polarizer in order to maintain the polarization and therefore the wavelength of laser operation. The radii of curvature of convex reflective surfaces 14, 15 are 120 cm. These mirrors, together with lens 13, establish a large intra-cavity beam diameter. An actual Nd:YLF laser in accordance with the construction of Figure 1 has achieved a  $TEM_{00}$  laser output of 40 watts, larger than any reported value to date.

There is no reason to limit the design of the present invention to only two pumping chambers and numerous such chambers operating in series are within the scope of the invention subject only to available intra-cavity space and input power.

Although the thermal focusing in Nd:YLF laser rods is small, it is unfortunately astigmatic, i.e. its magnitude and sign are different in the X and Y directions. Fig. 3 shows a single Nd:YLF laser rod with the direction of output shown by the arrow in the Z direction.

The difference in magnitude and sign of the thermal focusing in the X and Y directions has conventionally been corrected by employing an intracavity cylindrical lens in addition to the spherical lens used to expand the beam for large mode volume. The output beam produced by the use of a cylindrical lens is circularly symmetrical in the X-Y plane. Another prior way of achieving this correction with the arrangement of Fig. 1 is to make lens 13 a compound cylindrical-spherical lens with the cylindrical axis aligned to compensate for the astigmatism.

When pairs of Nd:YLF laser rods are placed in series, an alternative to the conventional use of a intracavity cylindrical lens is possible. By rotating one of the two collinear rods 90° relative to the other the astigmatic focusing of one rod can be used to correct for the astigmatic focusing of the other. However, this rotation alone results in

alignment of the polarization of the 1053nm beam from the first rod along the crystal C axis in the second rod which axis is appropriate for laser oscillation at a different wavelength (i.e. 1047 nm). This potential problem is corrected as shown in Fig. 4 by placing a half-wave plate at the 1053nm laser wavelength that results in the rotation by 90° of the linear polarization in the first rod (shown as arrow 1) to the position shown by arrow 2 so that the laser beam is always appropriately polarized along crystalline A axis to maintain the laser wavelength the same in both rods. The crystalline A axis is shown in Fig. 4 as the Y-axis.

In this way, assuming uniform thermal focusing from rod to rod, the total intracavity focusing in the X and Y direction is equal for each pair of rods so that the astigmatism discussed above is compensated without the need for a cylindrical lens. A two-headed Nd:YLF Laser built without an intracavity cylindrical lens and in accordance with this embodiment has yielded over 30 Watts of  $TEM_{00}$  mode power in a circularly symmetrical beam. Naturally this technique can be expanded to more than two rods, so long as they are in pairs.

While the invention above has described only CW lasers, it is obvious that an intra-cavity Q-switch or mode lock modulator, either acousti-optic or electro-optic, activated by an appropriate drive can be added to produce a Q-switched or a mode locked laser output. Figure 2 illustrates, in block form, an arrangement wherein the invention described in Figure 1 may be operated in Q-switched or a mode-locked mode; Q-switch 21 is operated by driver 20 to create Q-switching action. Similarly, mode locked output can be produced using an intracavity mode lock modulator.

While the foregoing description and accompanying drawings represent the preferred embodiments of the present invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the true spirit and scope of the present invention.

WHAT IS CLAIMED IS:

1. A high power  $TEM_{00}$  solid state laser comprising:  
2 a laser resonator with pumping chambers;  
3 at least two solid state laser rods mounted as coaxial-  
4 ly in series the pumping chambers within the resonator, said  
5 rods being constructed of a material having low thermal  
6 focusing and low thermal birefringence loss; and  
7 lens means within said resonator for expanding the beam  
8 to establish a large intra-cavity beam diameter and active  
9 volume, whereby a high  $TEM_{00}$  laser output is achieved.
- 1 2. The laser of claim 1, wherein said laser rods are  
2 constructed of Nd:YLF material.
- 1 3. The laser of claim 2, wherein said lens means for  
2 establishing a large intra-cavity beam diameter are a lens  
3 located between said two rods and resonator reflector surfaces  
4 at the ends of the resonator.
- 1 4. The laser of claim 3 wherein the lens is a  
2 compound cylindrical-convex lens with the cylindrical part  
3 aligned to compensate for astigmatic focusing of the laser  
4 rods.
- 1 5. The laser of claim 4 wherein the reflection  
2 surfaces are convex and have radii of curvature of about 120  
3 cm.
- 1 6. The laser of claim 3 wherein the lens is a  
2 cylindrical lens aligned to compensate for astigmatic focusing  
3 of the laser rods.
- 1 7. The laser of claim 2 further including a Q-switch  
2 means located in the resonator and a driver means connected to  
3 the Q-switch means for operating the laser in a Q-switched  
4 mode.

1                   8. The laser of claim 5 wherein the first and second  
2                   laser rods are shaped to be approximately 4 mm in diameter and  
3                   79 mm in length.

1                   9. The laser of claim 2 further including a predetermined  
2                   number of additional Nd:YAG rods mounted collinearly and  
3                   in series relationship within the resonator with appropriate  
4                   lens means for focusing the laser energy of one rod with  
5                   respect to the next so as to establish a large intra-cavity  
6                   beam diameter in order to achieve further increase in active  
7                   volume and,  $TEM_{00}$  laser power output.

1                   10. A high power  $TEM_{00}$  mode solid state laser comprising:

3                   a laser resonator with pumping chambers;  
4                   at least a pair of solid state laser rods mounted  
5                   in the pumping chambers and being arranged in series col-  
6                   linearly along a central laser axis, one of said pair of rods  
7                   being rotated 90° from the other about the laser axis, said  
8                   rods being constructed of a material having low thermal  
9                   focusing and low thermal birefringence loss;

10                  a half-wave plate at the laser wavelength aligned  
11                  collinearly along the laser axis and positioned between the  
12                  pair of rods for 90° polarization rotation; and

13                  lens means within said resonator for expanding the  
14                  beam to establish a large intra-cavity beam diameter and active  
15                  volume, whereby a high  $TEM_{00}$  laser output is achieved.

1                   11. The laser of claim 10, wherein said laser rods are  
2                   constructed of Nd:YLF material.

1                   12. The laser of claim 11 further including a Q-switch  
2                   means located in the resonator and a driver means connection to  
3                   the Q-switch means for operating the laser in a Q-switched  
4                   mode.

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FIG. 1

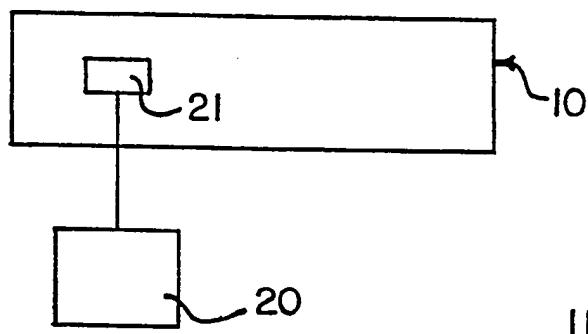
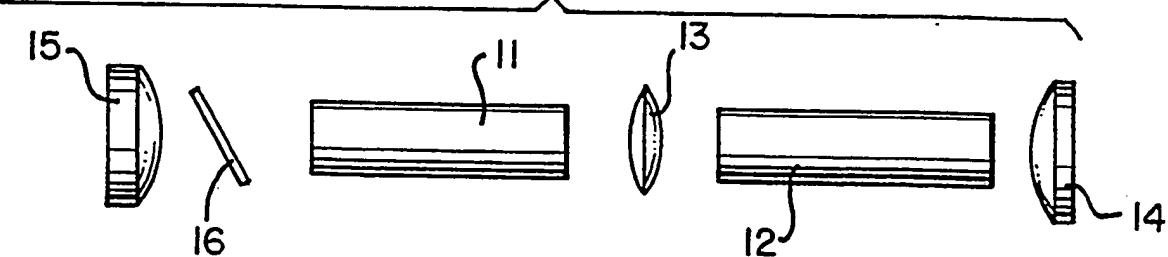


FIG. 2

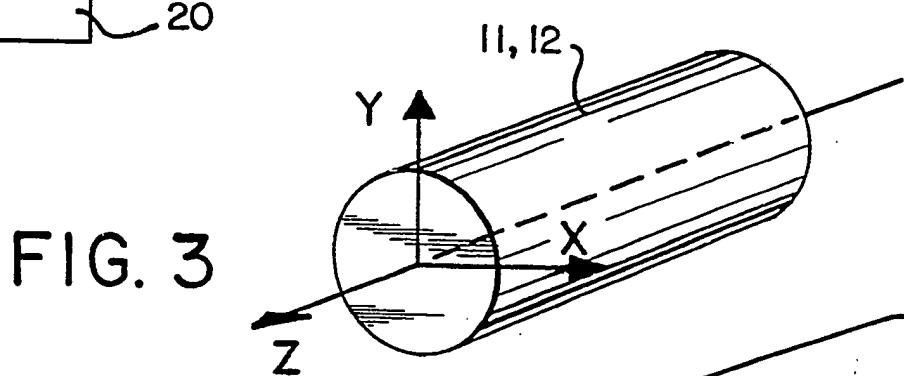
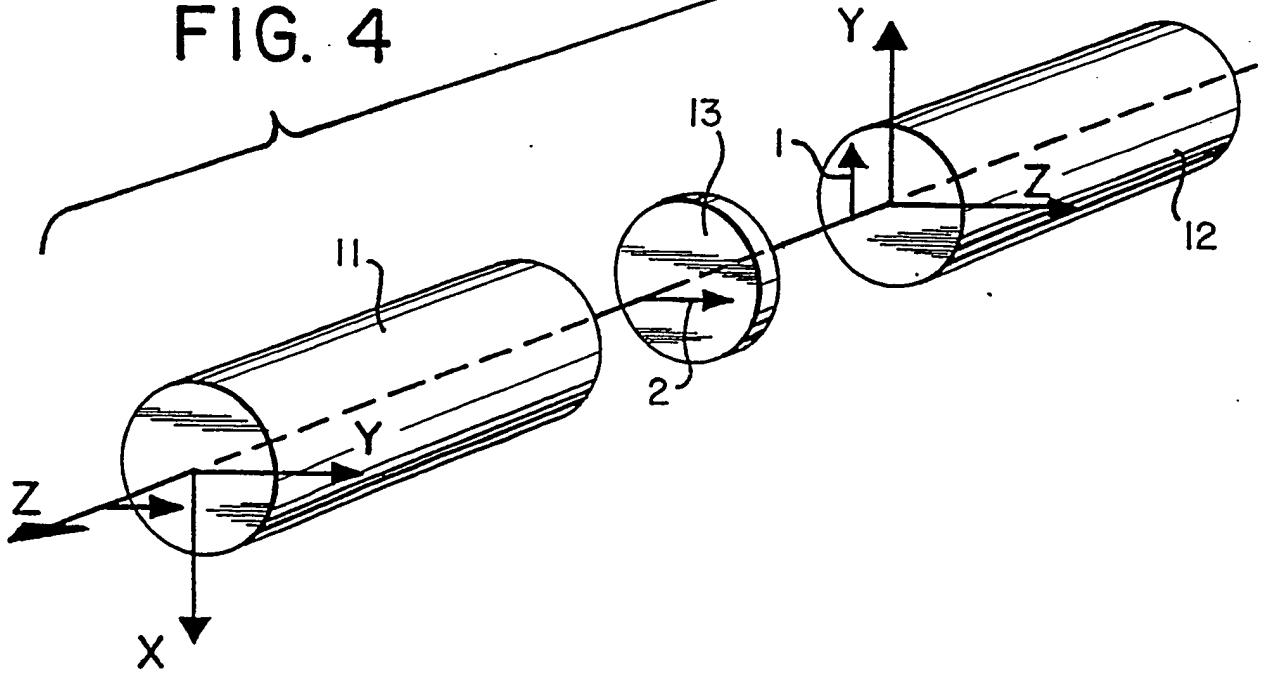


FIG. 3

FIG. 4



# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US90/02210

## I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) <sup>3</sup>

According to International Patent Classification (IPC) or to both National Classification and IPC  
 IPC(5) H01S 3/00  
 U.S.CL. 372/33

## II. FIELDS SEARCHED

Classification System <sup>4</sup>	Minimum Documentation Searched <sup>4</sup>	
		Classification Symbols
U.S.	372/97,33,68,40,41	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched <sup>5</sup>		

## III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>14</sup>

Category <sup>16</sup>	Citation of Document, <sup>16</sup> with indication, where appropriate, of the relevant passages <sup>17</sup>	Relevant to Claim No. <sup>18</sup>
X	US, A, 3,242,440 (KOESTER ET AL.) 22 March 1966 (Note figures 1 and 4).	1-12
A	US, A, 3,258,717 (KATZMAN) 28 June 1966 (See entire document).	
Y	US, A, 3,629,723 (SNITZER) 21 December 1971 (Note figure 6 and related disclosure).	10-12
Y	US, A, 4,352,186 (KUPPENHEIMER, JR. ET AL) 22 September 1982 (Note laser material being used).	2-9,11,12

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## IV. CERTIFICATION

Date of the Actual Completion of the International Search <sup>2</sup>

12 JULY 1990

International Searching Authority <sup>1</sup>

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Date of Mailing of this International Search Report <sup>2</sup>

07 AUG 1990

Signature of Authorized Officer

NGUYEN NGOC HO

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